



CLEMSON APPAREL RESEARCH

AUTOMATING INFORMATION EXTRACTION FROM 3D SCAN DATA

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DLA-ARN T2P5 Project Report

for
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Automating Information Extraction from 3D Scan Data
Contract No. SPO100-95-D-1002, DO0006
DLA Final Report

A. Contract Schedule Status Report

CAR is responsible for the following T2P5 Partner Activities:

1. Measurement/information definitions for CAR shirt
2. Macro language development
3. Information extraction from 3D Scans
 - (a) Software for auto-location of features/landmarks
 - (b) Software for measurements
 - (c) Software for shape evaluations
4. Software interface with CAR demonstration factory

Other Related Activities Accomplished: None.

B. Trips/Meetings

None.

C. Telephone Calls/Visitors/Contacts with Industry

None.

D. Progress Against Milestones

TASK 1. Measurement/information definitions for CAR shirt

Activity: This activity is complete.

TASK 2. Macro language development

Activity: This activity is complete.

TASK 3. Information extraction from 3D Scans.

Activities:

1. Body Part Identification:

This activity is complete.

2. Automatic Landmarking

This activity is complete.

3. Measurement

This activity is complete.

TASK 4. Software interface with CAR demonstration factory

This activity is complete.

E. Problem Areas - Technical/Schedule

None

F. Problem Areas – Cost

None

G. Problem Area Result

None

H. Changes

None

I. Engineering Change Proposal

None

J. Plans for the Following Period

None

Final Software Deliverables

With this report, CAR makes available executable copies of the *3DM* software package which run on a Silicon Graphics (SGI) workstation running Unix and on a PC running Windows NT. *3DM* is currently being refined for Tom and Linda Platt, Inc. of New York City for use in the design and development of high-end fashion women's garments. In addition, *3DM* is being considered for use with the scanner being developed by [TC]² of Raleigh, NC.

Final Report prepared by

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1. BACKGROUND AND RESEARCH OBJECTIVES

INTRODUCTION

The primary objective of this effort is to develop software that will manually and automatically extract traditional anthropometric measurements from three-dimensional point cloud data collected by a whole body scanner for design applications and to define algorithms to statistically summarize the results. The software package, called *3DM*, runs on a Silicon Graphics workstation running *Unix* and on a PC running *Windows NT*. *3DM* reads image files generated by *any* scanner that generates points in the form (x,y,z) where x , y , and z are the point coordinates in 3D. This includes files generated by a Cyberware WB4 scanner and a [TC]² Body Measurement System scanner. *3DM* currently allows a user to: (1) edit a 3D image, (2) display and manipulate the image, (3) manually identify, select, and segment regions, (4) manually select landmarks on the body, and using the landmarks, extract anthropometric measurements, and (5) automatically take anthropometric measurements specified by the user.

The benefits of software such as *3DM* include: (1) accuracy, consistency, and reliability of body measurement, (2) improved quality of garment fit, and (3) increased measurement speed. Military applications of *3DM* include: (1) automatic measurement of recruits and uniform issue at recruit induction centers at the start of basic training, (2) size prediction of recruits at the start of basic training for issue of uniform at the end of basic training, (3) monitoring of physical fitness of military personnel, (4) custom design of helmets for fighter pilots, (5) custom design of flight uniforms for fighter pilots, and (6) ergonomic design of workstations, including airplane cockpits and submarine quarters.

Commercial applications include: (1) automatic apparel size prediction from stock sizes, (2) affordable made-to-measure garment manufacturing, (3) design of ergonomically sound living space, workstations, and equipment, (4) custom-design of seats for automobiles, (5) monitoring of physical development of customers in physical fitness centers, (6) monitoring of physical development of athletes in school and professional sports, and (7) custom-design of artificial human limbs.

BACKGROUND AND RELATED WORK

Whole body scanning technology and related software are now commercially available. Companies which have developed whole body scanners include Cyberware (US), [TC]² (US), Vitronic (Germany), Telmat (France), NKK (Japan), and Hamamatsu (Japan). Companies which are currently building or which have proposed building whole body scanners include Rose Imaging (US), Global Structure (Netherlands), Dimension (Germany), RSI (Germany), Turing C3D (UK), and Laser Design (US). Simultaneously, a growing number of software packages designed to manipulate and analyze 3D whole body scans are now being developed. These include *CyScan*⁸ by Cyberware, Inc. *ShapeAnalysis*¹⁴ by Beecher Research Company, *DataSculpt*¹⁵ by Laser Design,

*Body Measurement System*⁹ by [TC]², *ARNScan*¹⁶ by a consortium of institutions supported by the Department of Defense, and a collection of software packages focusing on human engineering issues developed at the Armstrong Laboratory in Wright-Patterson Air Force Base¹⁷.

CyScan controls the Cyberware WB4 scanner and offers the user image manipulation and measurement tools. The model can be rotated, translated, scaled, converted into triangle strips, and displayed with multiple realistic lighting models. *CyScan* is written in OpenInventor, C++ and TCL/TK and is designed to run on SGI workstations. *Body Measurement System*, under development at TC², is designed to perform measurement extraction on scans generated by the [TC]² whole body scanner. This software is developed in Microsoft Developer Studio Visual C++ under the Windows NT platform and uses *OpenGL*¹⁰ graphics API to create the graphics display tools. The software provides a graphical user interface to control the acquisition sequence, acquire and store image buffers, process acquired images and calculating resulting data points, and display graphical output. A primary goal of [TC]² is to provide measurements required for apparel manufacturing automatically. *ShapeAnalysis* is a product of Beecher Research Company. *ShapeAnalysis* displays, manipulates, and analyzes data and allows users to obtain contour lengths, vector angles, surface areas, and volumes for enclosed areas. All distances are computed as straight lines and contour lengths are generated by algorithmically selecting specific points along a contour and summing the Euclidean distances between those points. Users generate contours by selecting three points on the model. The points are used to generate a plane which intersects the body in order to obtain a circumference measurement.

Clemson Apparel Research (CAR) has been working in the area of software development for 3D whole body scans since 1991. To date, algorithms have been developed in *3DM* for 3D scans generated by scanners from Dimensional Measurement Systems (DMS), Cyberware, and [TC]². The majority of the scans (over 200) used with *3DM* are Cyberware scans.

3DM

3DM^{1,3} is a software package that takes 3D whole body image files in text format and provides the user with functions to display, manipulate, segment, analyze, and measure the image. It is written in C++, uses *OpenGL* and *X-Windows* libraries, and runs on both an SGI workstation running *Unix* and on a PC running *Windows NT*.

A primary application of 3D whole body scanning technology has been apparel design⁴. *3DM* has focused on anthropometric measurement extraction for apparel design and for garment size prediction from a 3D whole body scan of a human being. *3DM* currently provides the user with tools to: (1) edit a 3D image generated by a scanner, (2) display and manipulate the image, (3) manually identify, select, and segment regions, (4) manually select landmarks on the body, and using the landmarks, (5) extract anthropometric measurements⁵⁻⁷ (with specific application to apparel design).

A user can read an input file containing points on the surface of the body, display the image, rotate along any dimension, translate along any dimension, and save selected points to an output file. Input files are in text format with each point represented by the ordered triple (x, y, z) where (x, y, z) are the floating-point coordinates of a point. If point color information is provided by the scanner, *3DM* reads a second triple (r, g, b) which represents the point's red, green, and blue color

coordinates. 3DM is scanner-independent and has been used with data generated by both Cyberware and [TC]² whole body scanners^{8,9}.

In *3DM*, a user can manually select any point, landmark, or series of points on the image (such as acromion, elbow, navel, etc.) and can take surface linear measurements, straight line measurements, and circumference measurements. Surface linear measurements follow the contour of the body, straight line measurements provide Euclidean distances between points, and circumference measurements may either follow the contour of the body or trace around the convex hull of the points.

3DM also provides segmentation functions. A user can select and isolate specific segments of the body with precision for detailed analysis. This allows the user to analyze the torso of the image, for example, without having to negotiate with the arms. Moreover, the user may select and analyze slices of the body taken at any angle. These slices may be viewed separately and provide, for example, detailed views of shoulder slopes and back postures.

The design of *3DM* is object-oriented. Two basic objects are a *point* and a *region* which is a set of points. A *region* is composed of a *region header* which contains global information about the region and a set of *region nodes*, each of which contains a pointer to a single point.

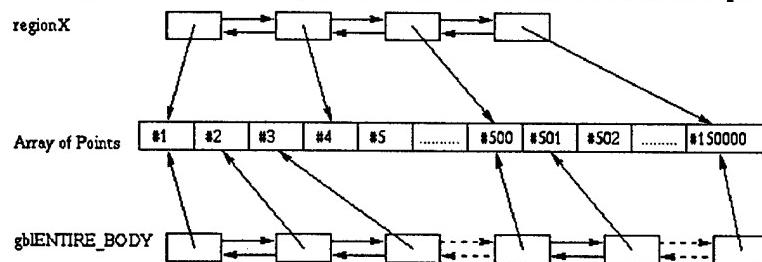


Figure 1. Regions in 3DM

and removed from *regions* without affecting the storage of the physical data points. This simple structure provides economy of storage and ease and flexibility in developing user functions. Only one copy of the data points is retained in computer memory; access to the points is accomplished through the use of pointers. This is important when dealing with the large number of points generated by whole body scanners. For example, Cyberware scanners typically generate over 150 thousand points. The [TC]² scanner can generate over 300 thousand points.

Figure 1 illustrates the general storage structure used in 3DM. Initially, all points are contained in the region *gblENTIRE_BODY*. Region X, for example, could be an arm, the torso, or the points on a slice through a leg. Points may be added to

Regions are dynamic sets of points and as such are easily modified. Points can be added to a region and removed from a region with ease. This allows, for example, rapid change from one slice to another through the body as the user focuses on a particular area of the image. Other functions in *3DM* smooth rough sections of the image. This is achieved by changing the values of the original data stored in the global array and has the effect of changing the data for all regions which access those points. Original images very often include extraneous points off the body generated by a scanner due to, for example, poor lighting. Such points may be eliminated from the region *gblENTIRE_BODY*, and after this region is saved, never need to be dealt with again. The bottom line is that working with regions has helped simplify code development in *3DM*.

Development continues on *3DM*. Work is underway on (1) automatic identification of landmarks, (2) automatic extraction of measurements, (3) introduction of whole body images into a virtual reality environment for design of industrial and military work areas, and (4) introduction of animation functions for studies involving interaction of multiple human images in close working

environments. The need for automation is compelling. Automatic computation of a person's measurements is necessary if 3D scanning technology is to succeed in the commercial marketplace. Automatic measurement extraction can be used effectively in military recruit training centers each of which may handle several thousand recruits in a month. Many possibilities in mass marketing arise when automatic measurement extraction is perfected. Introduction of 3D whole body images in virtual reality environments provides an added dimension of realism to a virtual scene. The goals are to allow more than one image in a scene, to animate the images, and to allow images to interact with one another.

MANUAL MEASUREMENT EXTRACTION

Manual measurement extraction is achieved in *3DM* through the combination of several functions: (1) point selection, (2) segment selection, (3) segment extraction, (4) point-to-point surface linear measurement, (5) point-to-point straight-line linear measurement, (6) surface circumference measurement, (7) convex hull circumference measurement, (8) elimination of extraneous points, and (9) the use of tilted planes.

The tilted-plane function is particularly useful because it allows the user to take a slice through the body and tilt it in any direction and by any angle. This allows selection, for example, of waist and bust slices that conform to the specific shape of the image. Once a slice is selected, the desired measurement may be obtained. The mathematical basis for the concept and use of tilted planes is described in the paper *Tilted Planes in 3D Image Analysis* shown in Appendix A of this document.

AUTOMATIC MEASUREMENT EXTRACTION

This section describes the approach used for automatic measurement extraction. It includes a description of an overall approach and a detailed technical discussion of specific algorithms for some of the measurements. This discussion also provides preliminary results achieved in *3DM* using over 200 Cyberware WB4 images available to CAR investigators.

Approach

This algorithmic approach used in *3DM* is a *top-down* approach to automatic measurement extraction. The approach consists of six major steps. Given a scan produced by either a Cyberware WB4 or a [TC]² whole body scanner, *3DM* will proceed to: (1) *clean* the image data, (2) *orient* the image correctly so that the resulting image is in a standard orientation, (3) determine the *gender* of the subject, (4) generate a set of gender-dependent *approximate height locations* on the image which, in effect, partition the image, (5) identify a set of *landmarks* using the approximate height locations, and (6) *extract* measurements based on the landmarks identified. All of these steps will be performed *automatically* without user intervention. The user, of course, will have the option of manually modifying the result of any step, if desired.

A strength of the approach lies in the fact that, by the *critical* fifth step of landmark identification, the image has been cleaned, reoriented if necessary, classified by gender, and partitioned into relatively small segments. During landmark identification, precise algorithms, relying on a variety of mathematical functions, can focus on small segments of the body and can be hand-crafted for each landmark.

The final step, measurement extraction, is a straightforward process using tools already in *3DM* to take either Euclidean or surface linear measurements, or circumferences which either follow the contour of the body or the convex hull (rubber band) around the body slice. An explanation of each step follows.

(1) *Clean the image*

Image files generated by whole body scanners frequently include extraneous points outside the body. These unwanted points are the result of various problems, primarily due to poor lighting. Figure 2 shows a raw image generated by a Cyberware WB4 scanner. (Unless necessary to illustrate a point, heads of images have been removed to protect the privacy of the subjects involved. Permission has been granted by those individuals whose faces are shown.) Figure 3 shows the same image after the undesired points are removed. Starting with a clean image is essential to the success of automatic measurement extraction because algorithms in *3DM* depend on maximum and minimum values along the *x*-, *y*-, or *z*-axes. Extraneous points give false extrema resulting in erroneous algorithms.

(2) *Orient the image*

Once the image is clean, the orientation of the image is, if necessary, automatically corrected. Orienting the image significantly improves the accuracy of the algorithms used for landmark detection and subsequent, measurement extraction. Figures 4 and 5 show images correctly oriented. Note that the origin is located within the body. The *z-axis* is vertical with the positive and negative *z-axes* emerging through the top of the head and the crotch, respectively. The positive and negative *x-axes* are horizontal located near the midsection of the image and emerging from the right hand and left hand side of the body, respectively. Finally, the positive and negative *y-axes* extend from the front and the back of the image, respectively.

After this step, the *xy-plane* divides the image into two parts: upper-half and lower-half. The *yz-plane* divides the image into left-half and right-half. The *xz-plane* divides the image into front and back. Orienting the image in this manner simplifies algorithm development significantly.

(3) *Determine the gender of the image*

Relative locations of various landmarks are gender-dependent¹¹⁻¹³. For example, the median height of a person's shoulder reported to be 0.82 of the person's stature if male and 0.81 if female¹¹. Similarly, the median waist height is reported to be 0.61 of a person's stature if male and 0.63 if female. Identifying locations and landmarks such as the bustline and bust points will require different algorithms depending upon whether the image is male or female. Moreover, the median waist/hip ratio¹² is significantly larger for males (0.9) than for females (0.78).

All of this suggests that automatic detection of the gender of the image may prove useful in providing clues to locating landmarks. The development of an algorithm to determine the gender of an image is a primary goal of this project.

(4) Generate approximate height locations on the image

Once the gender is determined, 3DM estimates the heights of sixteen locations on the body. These height estimates are: (1) eye, (2) neck, (3) shoulder, (4) cross chest, (5) armpit, (6) bustline, (7) diaphragm, (8) elbow, (9) waist, (10) high hip, (11) mid hip, (12) low hip, (13) knuckle, (14) crotch, and (15) thigh, and (16) knee. 3DM also makes one vertical estimation: body center. Examples of these initial estimates, automatically determined, on a male and a female image are shown in Figures 6 and 7.

The estimates are obtained by applying, for each height approximation, a predefined fraction to the stature of the image. Table 1 gives the values of the fractions applied to Figures 6 and 7. If the stature of the image is equivalent to 1.00, then the eye height is estimated to be at 0.94 (94% of the person's height) for males and 0.93 for females. Similarly, the thigh is estimated to be at level 0.41 for both males and females. Note that for females, both the elbow and the waist are estimated to be at level 0.63. Hence there are sixteen horizontal lines (representing sixteen height estimates) in Figure 6 and fifteen horizontal lines in Figure 7.

The values in Table 1 are continually being improved as feedback from testing of 3DM is received. The fractions shown in Table 1 were initially obtained from textbooks and references on physical measurements¹⁰⁻¹³. Modifications were made after approximation algorithms were tested on 200+ Cyberware WB4 whole body images and the estimates were evaluated for accuracy. The objective of the testing process is, for each estimate, to converge to a fraction which represents a median value for the population under study.

The purpose of these estimates is to provide *starting points* for the landmark identification algorithms described in Step 5. The estimate is not intended to provide the exact height of a landmark for every image. The purpose is to provide a starting location for a more careful search. The next step is to work with an estimate to locate a desired landmark.

(5) Identify landmarks on the image

After Step 4, 3DM has sixteen height estimates with which to work. In addition, the orthogonal planes (from Step 2) halve the image three different ways. Using these estimates, refined algorithms can be developed for each landmark, height, measurement, or circumference desired. Examples of landmark identification algorithms currently being tested in 3DM are provided in the Technical Discussion below. Snapshots showing the results of the algorithms are shown in Figures 8-25.

	Male	Female
Eye	0.94	0.93
Neck	0.86	0.84
Shoulder	0.82	0.81
Cross Chest	0.79	0.79
Armpit	0.75	0.75
Bustline	0.72	0.72
Diaphragm	0.70	0.70
Elbow	0.63	0.63
Waist	0.61	0.63
High Hip	0.58	0.58
Mid Hip	0.53	0.53
Low Hip	0.49	0.49
Knuckle	0.43	0.44
Crotch	0.47	0.47
Thigh	0.41	0.41
Knee	0.26	0.28

Table 1

(6) Take measurements

From the landmarks obtained in Step 5, measurements can be taken in 3DM in a straightforward manner. Functions already exist to take (1) straight line (Euclidean) measurements between any two points on or off of the image, (2) surface or contour measurements between any two points both of which lie on the image body, (3) circumference measurements which follow the contour of the body, and (4) circumference measurements which follow the convex hull of the body. All that remains to be done is to call the required function with the appropriate landmarks obtained in Step 5.

A summary of the tasks accomplished in this project are listed below.

1. Analysis of Past Work Related to Automatic Measurement Extraction

This task will review previous and current efforts at automatic measurement extraction from 3D whole body images. This includes efforts in the U.S., in Europe, and in Japan.

2. Collection of Data

A set of 200+ Cyberware WB4 images was collected for this project. These images were used to refine the algorithms so that the final algorithms will work correctly on a wide spectrum of body shapes and sizes, *including* the standing and seated scans provided by the U.S. Navy.

3. Image Preparation Algorithms

Algorithms were developed and refined to clean, orient, and classify 3D images. This corresponds to Steps 1-3 described above.

4. Landmarking and Measurement Algorithms

The major portion of this effort involved the development of algorithms to select points on the body and to take measurements based on these points.

TECHNICAL DISCUSSION

This section provides *results* of seven algorithms used to locate landmarks shown in Figures 8-25. As examples, Algorithms #1 and #2 (navel, narrowest waist) are described in detail to give the reader a sense of the steps used to identify landmarks. For all of the algorithms, it is assumed that Steps 1-4 have been performed, i.e., (1) the image has been cleaned, (2) the image is correctly oriented, (3) the image has been classified by gender, and (4) initial height approximations have been taken. Moreover, images are assumed to have heads. Other requirements may apply and are specified with each algorithm.

These algorithms represent a fairly recent attempt by the CAR research team in automatic landmark identification and measurement extraction. As shown below, the preliminary results are very encouraging. Continued refinement of the algorithms will lead to steadily improving success rates. The evaluation is led by one member of the CAR research team whose primary

responsibility is the testing and evaluation of algorithms developed by other members of the team. His evaluation is given to the CAR software developers who then work to correct the mistakes reported by the evaluator.

The purpose of this section is to give the reader a clearer understanding of the general approach used in the landmark identification algorithms of *3DM*.

Algorithm #1

Name: Navel
Status: Implemented
Images: 107 (81 male, 26 female)
Test Results: 93% success on 81 male images (75/81)
85% success on 26 female images (22/26)
Requirements: Navel must be exposed on image
Remarks: None

Algorithm:

1. Start with waist height estimate
2. From entire body, select all points with z-values within a given distance (e.g., ± 6.0 cm) of waist height
3. From (2), select points with positive y-values
4. From (3), select points whose x-values are within a given distance (e.g., ± 2.0 cm) from the origin
5. Sort each horizontal slice (same z-value) by x-value
6. Calculate the slopes between consecutive x-values for each slice
7. Calculate the differences between consecutive slopes for each slice
8. Find the most positive slope difference in region (indicating greatest concavity)
9. Where concavity is greatest, choose point with least y-value; call this point the navel

The identification of the navel using Algorithm #1 was judged good in 93% (male) and 85% (female) of the images tested. Snapshots of results judged good are shown in Figures 8a and 8b. In those cases which were judged bad, either (a) the indentation of the navel was shallow, or (b) prominent markers were placed on the body. Because the algorithm is based on slope differences, the algorithm will either (a) not detect a significant change in slope at the navel, or (b) erroneously choose a point near a marker. Figure 9 shows an example of an error due to shallow navel indentation.

Correct identification of the navel can be used to determine a waist circumference at that height (see Gordon *et al.*, NATICK/TR-89/044, page 300). Alternatively, Algorithm #2 below may be used to select the waist measurement with the narrowest circumference (see Gordon *et al.*, NATICK/TR-89/044, page 298). In either case, waist height can be used to identify and select a left or right waistline point, which, in turn, can be used to take a "waist-to-floor" measurement. A function to take a linear surface measurement along the lateral curve of the leg is already available in *3DM*.

Algorithm #2

Name: Locate waist at point of narrowest circumference
Status: Implemented
Images: 169 (97 male, 72 female)
Test Results: 99% success on 97 male images (96/97)
 99% success on 72 female images (71/72)
Requirements: Image must be standing with arms slightly away from torso
Remarks: None
Algorithm:
1. Start with waist height estimate and a range of points above and below
2. Select all points on torso between minimum and maximum Z-values
3. Let region L = set of points with the most positive X-values for each z-slice
4. Let region R = points with the most negative x-values for each z-slice
5. Let region W = points with the most negative y-values for each z-slice
6. Let point A = point in region L with the least positive x-value
7. Let point B = point in region R with the least negative x-value
8. Let point C = point in region W with the least negative z-value
9. Using the Z-values of points A, B, C, find the Z-value where the straight-line distance across torso is the least
10. The Z-slice taken at this Z-value is the narrowest waist

Algorithm #2 proved to be quite successful; in 99% of the images, both male and female, the placement of the waist was judged to be good. Figures 10a and 10b show examples. The algorithm did not always place the waist on the elastic waistband (for those images which had a waistband). It looked for what it considered to be the narrowest circumference. Figure 11 shows the only female image for which the algorithm's waist placement was judged less than perfect. The algorithm missed the elastic waistband which, in this image, appears to be the where the narrowest circumference lies.

Algorithm #3

Name: Center back point at neck (~cervicale)
Status: Implemented
Images: 107 (all male)
Test Results: 71% success on 107 male images (76/107)
Requirements: Unobstructed view of back of neck (long hair not allowed)
 Hands and arms may not be beside or above head
Remarks: Tested only on male images

Algorithm #3 searches for the center back point at neck (~cervicale). Figures 12a and 12b show snapshots of results on a male and a female image. The center back point at neck and the acromion (Algorithm #4) are two landmarks necessary for a sleeve length measurement.

Success, to date, has been fair (71% on 107 male images). The algorithm correctly locates the height of the point over 90% of the time. Most of the placements judged bad have been due to improper placement to the left or to the right of the correct location. Figure 13 shows a poor placement.

Algorithm #4

Name:	Left and Right Acromion
Status:	Implemented
Images:	178 (107 male, 71 female)
Test Results:	75% success on 107 male images (80/107) 79% success on 71 female images (56/71)
Requirements:	Hands and arms may not be beside or above head
Remarks:	None

Figures 14 and 16 show examples of this algorithm's placement of the left and right acromion. The estimates in Figure 14 are judged to be good; those in Figure 16 are judged to be bad, judged slightly lower on the arms than they should be. Note that the objects in Figure 16 protruding above the shoulders are part of the scan; these were physical markers placed on the body when the scan was taken. Because this algorithm analyzes characteristics of points along the left and right shoulders of the image, the presence of these markers contributed to the algorithm's failure to locate the landmarks. The overall success rate of 76%, for a first attempt, is encouraging.

From the acromion points, it is immediately possible to take a back width measurement. Examples are shown in Figures 15 and 17 which use the acromion landmarks shown in Figures 14 and 16, respectively. Judging from the image, the back width measurement in Figure 17, taken from what were judged to be poor acromion points (Figure 16), may turn out to be an acceptable measurement. Refinement of this algorithm continues in an effort to improve the overall success rate.

Algorithm #5

Name:	Crotch
Status:	Implemented
Images:	74 (female)
Test Results:	61% success (45/74)
Requirements:	Standing
Remarks:	None

The crotch was a difficult landmark to locate. The variety of body shapes and forms ranging from very slim teenagers, to physically fit young men and women to heavy, to middle-aged men and women, clearly showed that the crotch algorithm had to handle a large number of possible shapes in the lower torso/upper leg area of the body. At this point, testing has been done only on female images. The overall success rate is 61%. Figures 18-20 show sample results. Figure 18 is a good result and relatively easy to find because of the good physical fitness of the image. Figure 19 is also a good result despite the fact that the body shape was much heavier. Figure 21 shows a bad result due primarily to the lack of smoothness and irregularity of shape in the crotch area of this image (seen more clearly close up).

The results are encouraging because this is a difficult landmark to locate and the algorithm used is a fairly simple and straightforward analysis of planes parallel to the *yz-plane* in the region of the body between the thigh and the low hip. Part of the problem is that the crotch is a part of the

body partially obscured from scanner view by the legs. As a result, in many images, relatively few points can be found in the crotch area. Refinement of the algorithm has begun and improved results should be forthcoming.

Algorithm #6

Name:	Bustline
Status:	Implemented
Images:	74 (female)
Test Results:	100% success (74/74)
Requirements:	Arms must not be raised; they may, however, be slightly away from the torso; standing
Remarks:	None

The results for Algorithm #6 are very good, reporting 100% success among 74 images. Identification of the bustline leads directly to the chest circumference measurement. Figures 21-24 show front and side views of the results on two female images. (Please note that Figures 22 and 24 are a bit misleading in that the circumference appears to go around the arms. The circumference measures *only* the chest and does *not* include the arms.) To date, the algorithm has been used only on female images. A different algorithm will be used to locate the chest circumference on male images.

Algorithm #7

Name:	Bideltoid
Status:	Implemented
Images:	43 (30 male, 13 female)
Test Results:	93% success on 30 male images (28/30) 92% success on 13 female images (12/13)
Requirements:	Arms must be close to body and not raised
Remarks:	None

Figures 25a-c show results of the bideltoid measurement. Success rates of 93% for males and 92% for females were achieved. Figures 25a and 25b show results judged good on male and female images, respectively. Figure 25c shows a male figure bideltoid placement judged slightly high.

Summary

Table 2 summarizes the results of seven algorithms presented in this report. The percentage is the success rate; the numerator is the number of images judged good whereas the denominator is the number of images tested. These algorithms represent a first attempt at automatic extraction of these landmarks and measurements in 3DM. The results are quite encouraging; with refinement, they will certainly improve. This suggests that the overall approach is sound and holds great promise.

	Male	Female
Navel	93% (75/81)	85% (22/26)
Waist	99% (96/97)	99% (71/72)
Cervicale	71% (76/107)	
Acromion	75% (80/107)	79% (56/71)
Crotch		61% (45/74)
Bustline		100% (74/74)
Bideltoid	93% (28/30)	92% (12/13)

Table 2

H. Potential Post Applications

Military and Commercial

The human environment, from the nearest (clothing) to the greatest (work and living spaces) has typically been designed using human body dimensions. The availability of consistent, accurate dimensions for large numbers of subjects, without the prohibitively expensive investment of manpower and monetary resources associated with traditional anthropometric surveys, opens up a wide variety of both military and commercial applications. In general, these applications will all realize an improvement in design quality. These data will certainly revolutionize processes for some.

Clothing the human body has traditionally depended on linear measurements. Deriving these measurements more precisely, and having access to these measurements for large samples of populations, can lead to manufacturers doing a better job of developing apparel patterns. These patterns will produce garments which reflect actual body configurations of target customers. This includes the extremes of 18- to 25-year-old military recruits who need individual and protective clothing and senior adults who have experienced physical changes attributable to aging but who want to look attractive and feel comfortable in fashionable clothing.

If the application is for *stock* clothing sizes, with good anthropometric data the decision of what assortment to place in inventory can be refined to avoid stock outs and excesses. The process of selecting a correct size can be streamlined; a computer expert system can suggest the nearest fitting size in a given style, for example.

If the application is for *made-to-measure*, the body dimensions can be automatically processed for pattern making by feeding measurement extraction output into made-to-measure software. The possibility also exists that non-traditional measurements which are impossible to capture with traditional tools on a live human, but which could greatly improve the fit of clothing, can be derived easily on the computer. In addition, information such as shapes (the intersection of the body with a plane in any dimension) can be analyzed to produce better pattern configurations and, therefore, fit. The shortening of the order processing time for made-to-measure can make it possible for *all* clothing (military or commercial) to be made for the individual, eliminating stock entirely. If it is possible to get what you want in the correct size in a timely manner and at the right price, why buy stock?

The spaces where humans live and work have also traditionally been created using linear measurements. As with clothing, the design of these environments can be created in more appropriate *generic* configurations or *tailored-to-fit* as never before because of the accuracy of measurements and the accessibility of data not previously available. The analyses of shapes and body measurements in postures not associated with traditional anthropometry, such as the position of the body during military operations (flying airplanes, jumping or ejecting out of airplanes, driving tanks) can also be made possible by scans of the body while simulating these activities. Interactive measurement tools currently available in 3DM would be useful in developing automated tools for these postures in Phase II.

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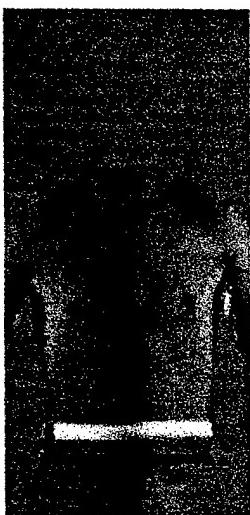


Figure 10a



Figure 10b



Figure 11

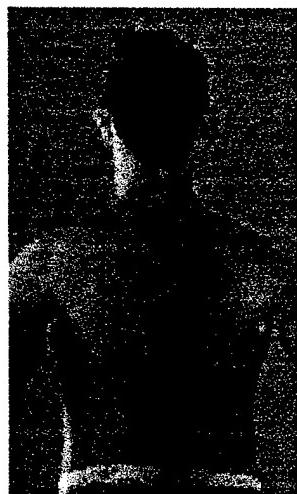


Figure 12a

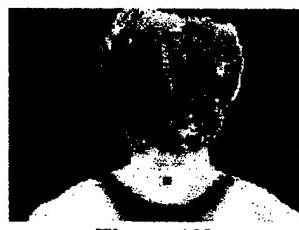


Figure 12b



Figure 13

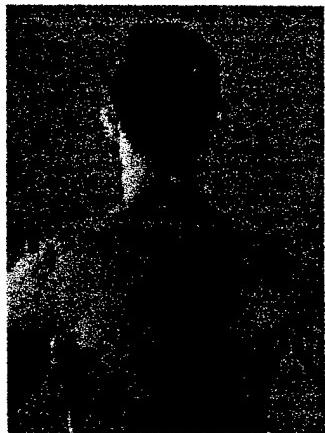


Figure 14



Figure 15



Figure 16



Figure 17



Figure 18



Figure 19



Figure 20



Figure 21



Figure 22



Figure 23



Figure 24



Figure 25a

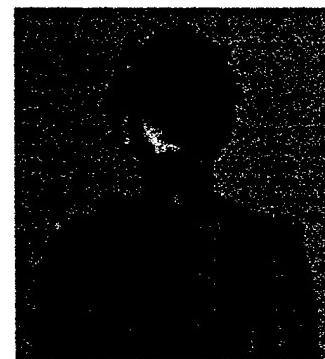


Figure 25b



Figure 25c

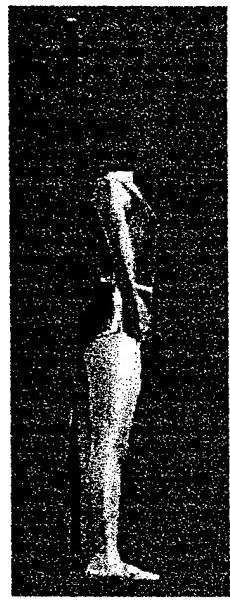


Figure 2



Figure 3



Figure 4



Figure 5



Figure 6



Figure 7



Figure 8a



Figure 8b



Figure 9

APPENDIX A

Tilted planes in 3D image analysis

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ABSTRACT

Reliable 3D wholebody scanners which output digitized 3D images of a complete human body are now commercially available. This paper describes a software package, called *3DM*, being developed by researchers at Clemson University and which manipulates and extracts measurements from such images. The focus of this paper is on tilted planes, a *3DM* tool which allows a user to define a plane through a scanned image, tilt it in any direction, and effectively define three disjoint regions on the image: the points on the plane and the points on either side of the plane. With tilted planes, the user can accurately take measurements required in applications such as apparel manufacturing. The user can manually segment the body rather precisely. Tilted planes assist the user in analyzing the form of the body and classifying the body in terms of body shape. Finally, tilted planes allow the user to eliminate extraneous and unwanted points often generated by a 3D scanner. This paper describes the user interface for tilted planes, the equations defining the plane as the user moves it through the scanned image, an overview of the algorithms, and the interaction of the tilted plane feature with other tools in *3DM*.

Keywords: Anthropometric measurement, 3D whole body scanning, CAD, apparel manufacturing

1. INTRODUCTION

Whole body scanning technology and related software are now commercially available. Companies which have developed whole body scanners include Cyberware (US), TC² (US), Vitronic (Germany), TecMath (Germany), Telmat (Netherlands), NKK (Japan), and Hamamatsu (Japan). Companies which are currently building or which have proposed building whole body scanners include Rose Imaging (US), Global Structure (Netherlands), Dimension (Germany), RSI (Germany), Turing C3D (UK), and Laser Design (US)¹. Simultaneously, a growing number of software packages designed to manipulate and analyze 3D whole body scans are now being developed. These include *CyScan*² by Cyberware, Inc. *ShapeAnalysis*³ by Beecher Research Company, *DataSculpt*⁴ by Laser Design, *Body Measurement System*⁵ by TC², *ARNScan*⁶ by a consortium of institutions supported by the Department of Defense, a collection of software packages focusing on human engineering issues developed at the Armstrong Laboratory in Wright-Patterson Air Force Base⁷, and *3DM*^{8,9} by Clemson University.

CyScan controls the Cyberware WB4 scanner and offers the user image manipulation and measurement tools. The model can be rotated, translated, scaled, converted into triangle strips, and displayed with multiple realistic lighting models. *CyScan* is written in OpenInventor, C++ and TCL/TK and is designed to run on SGI workstations.

Body Measurement System, under development at TC², is designed to perform measurement extraction on scans generated by the TC² whole body scanner. This software is developed in Microsoft Developer Studio Visual C++ under the Windows NT platform and uses *OpenGL*¹⁰ graphics API to create the graphics display tools. The software provides a graphical user interface to control the acquisition sequence, acquire and

store image buffers, process acquired images and calculating resulting data points, and display graphical output. A primary goal of TC² is to provide measurements required for apparel manufacturing automatically.

ShapeAnalysis is a product of Beecher Research Company. *ShapeAnalysis* displays, manipulates, and analyzes data and allows users to obtain contour lengths, vector angles, surface areas, and volumes for enclosed areas. All distances are computed as straight lines and contour lengths are generated by algorithmically selecting specific points along a contour and summing the Euclidean distances between those points. Users generate contours by selecting three points on the model. The points are used to generate a plane which intersects the body in order to obtain a circumference measurement.

3DM is a software package being developed at Clemson University. In development since 1991, it takes 3D whole body image files in text format and provides the user with functions to display, manipulate, segment, analyze, and measure the image. It is written in C++, uses *OpenGL* and *X-Windows* libraries, and runs on both an SGI workstation running *Unix* and on a PC running *Windows NT*. *3DM* is described in greater detail in Section 2 below.

This remainder of this paper describes *3DM*, focusing on a specific function, *tilted planes*, as used in the package. Section 2 describes *3DM* in greater detail. Section 3 describes the mathematical foundation for tilted planes, the equations defining the plane as the user moves it through the scanned image. Section 4 provides an overview of the algorithms and the interaction of the tilted plane feature with other tools in *3DM*. The paper concludes with final remarks and future work.

2. 3DM

2.1 Current status

A primary application of 3D whole body scanning technology has been apparel design¹⁶. Clemson University is involved in developing software for measurement extraction and garment size prediction from a 3D whole body scan of a human being. The goal of this research project is to provide the user with tools to: (1) edit scanner output, (2) display and manipulate the data, (3) identify, select, and segment regions, (4) identify landmarks on the body, and (5) extract anthropometric measurements^{11,12,14,15} with specific application to apparel design.

All of these functions are now available in *3DM*. A user can read an input file containing points on the surface of the body, display the image, rotate along any dimension, translate along any dimension, and save selected points to an output file. Input files are in text format with each point represented by the ordered 6-tuple (x, y, z, r, g, b) where (x, y, z) are the floating-point coordinates of a point and (r, g, b) are its red, green, and blue color coordinates. As such, *3DM* is scanner independent and has been used with data generated by both Cyberware and TC² whole body scanners.

A user can select any landmark on the body such as acromion, neck and shoulder intersection points, center back point at the neck, elbow, wrist, navel, and crotch. With these landmarks the user can take surface linear measurements, straight line measurements, and circumference measurements such as neck circumference, back width, acromial height, sleeve length, chest circumference, diaphragm circumference, waist circumference at navel, waist circumference at narrowest point, preferred waistline, hip circumference, seat circumference, crotch height, waist to floor along lateral curvature of leg, knee height at midpatella, shoulder circumference, and inseam length. Surface linear measurements follow the curvature of the body, straight line measurements provide Euclidean distances between points. Circumference measurements may either follow the contour of the body or trace around the convex hull of the points.

3DM also provides segmentation functions. A user can select and isolate specific segments of the body with great precision for detailed analysis. This allows the user to analyze the torso of the image, for example, without having to negotiate with the arms. Moreover, the user may select and analyze slices of the body

taken at any angle. These slices may be viewed separately and provide, for example, detailed views of shoulder slopes and back postures. Segmentation and slice analysis are two benefits derived directly from the use of *tilted planes* and are discussed further in Section 4.

2.2 Regions in 3DM

The design of 3DM is object-oriented. Two basic objects are a *point* and a *region* which is a set of points. A *region* is composed of a *region header* which contains global information about the region and a set of *region nodes*, each of which contains a pointer to a single point.

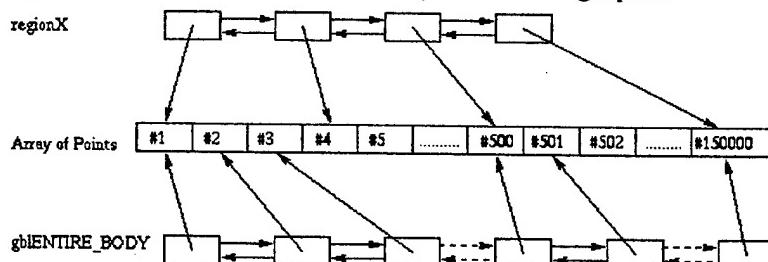


Figure 1. Regions in 3DM

storage of the physical data points. This simple structure provides economy of storage and great ease and flexibility in developing user functions. Only one copy of the data points is retained in computer memory; access to the points is accomplished through the use of pointers. This is important when dealing with the large number of points generated by whole body scanners. For example, Cyberware scanners typically generate over 150 thousand points. The TC² scanner generates over 300 thousand points.

Figure 1 illustrates the general storage structure used in 3DM. Initially, all points are contained in the region *gb!ENTIRE_BODY*. Region X, for example, could be an arm, the torso, or the points on a slice through a leg. Points may be added to and removed from regions without affecting the

Regions are dynamic sets of points and as such are easily modified. Points can be added to a region and removed from a region with ease. This allows, for example, rapid change from one slice to another through the body as the user focuses on a particular area of the image. Other functions in *3DM* smooth rough sections of the image. This is achieved by changing the values of the original data stored in the global array and has the effect of changing the data for all regions which access those points. Original images very often include extraneous points off the body generated by a scanner due to, for example, poor lighting. Such points may be eliminated from the region *gbIENTIRE_BODY*, and after this region is saved, never need to be dealt with again. The bottom line is that working with regions has helped simplify code development in *3DM*.

2.3 Work in Progress

Development continues on 3DM. Current work includes (1) automatic identification of landmarks, (2) automatic extraction of measurements, (3) introduction of whole body images into a virtual reality environment for design of industrial and military work areas, and (4) introduction of animation functions for studies involving interaction of multiple human images in close working environments. The need for automation is compelling. Automatic computation of a person's measurements is necessary if 3D scanning technology is to succeed in the commercial apparel market. Many possibilities in mass marketing arise when automatic measurement extraction is perfected. Introduction of 3D whole body images in virtual reality environments provides an added dimension of realism to a virtual scene. The goals are to allow more than one image in a scene, to animate the images, and to allow images to interact with one another.

Automatic landmarking and measurement will be complete by the end of the Spring semester, 1998. The initial results in the work on animation will be available by the end of the Summer 1998 term.

3. PLANES

3.1 Overview

Operations on a 3D scan of a human body can involve considerable use of planes. For example, circumference measurements are typically planar measurements. This section briefly describes the concept of *direction numbers* of a line and how they may be effectively used to control planes in space.

3.2 Direction numbers

Consider a line L in three dimensional space shown in Figure 2. Angles α , β and γ between line L and the positive x' , y' , and z' -axes respectively are called *direction angles* of L . The values $\cos \alpha$, $\cos \beta$, and $\cos \gamma$ are called *direction cosines* of L ¹³. Any line in space can be uniquely identified using its direction cosines and a point on the line. Three numbers l , m , and n , not all zero, are *direction numbers* of a line L if there exists a number r such that $l = rl'$, $m = rm'$, $n = rn'$, where l' , m' , and n' are the direction cosines of the line L .

3.3 Equations of planes

A line perpendicular to a plane is called a *normal line* of the plane. Let line L with direction numbers a , b , and c , be normal to plane p , and let L and p intersect at point $Q(x_1, y_1, z_1)$ as shown in 3. A point $P(x, y, z)$ distinct from Q is on the plane if and only if the line K through P and Q is perpendicular to L . Since the line K has direction numbers $x - x_1, y - y_1, z - z_1$, P is on plane p if and only if

$$a(x - x_1) + b(y - y_1) + c(z - z_1) = 0 \quad (1)$$

that is, if and only if L and K are perpendicular. Hence the equation of plane p is of the form

$$ax + by + cz + d = 0 \quad (2)$$

where $d = -(ax_1 + by_1 + cz_1)$.

3.4 Tilted planes

Tilting a plane merely involves modifying the direction angles of L . Once again, consider a plane p with a normal line L passing through $Q(x_1, y_1, z_1)$. Let the line L have direction angles α , β , and γ . Let a , b , c be the direction cosines of L ; i.e. $a = \cos \alpha$, $b = \cos \beta$, and $c = \cos \gamma$.

Consider the simplified view shown in Figure 4. The x - and z -axes are shown; the y -axis is perpendicular to the printed page. Plane p is represented by the solid horizontal line; the goal is to rotate the plane by an angle θ about the line passing through Q

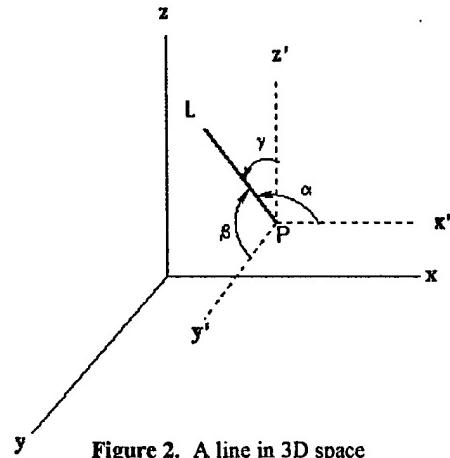


Figure 2. A line in 3D space

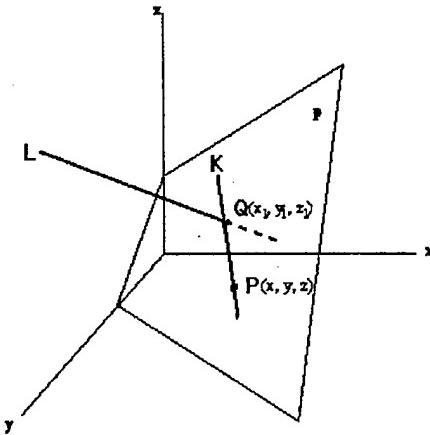


Figure 3. Plane p with normal line L

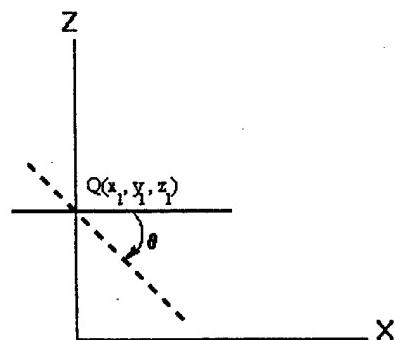


Figure 4. Tilting a plane

and perpendicular to the xz -plane. The result is the plane p' represented by the dashed line. To achieve this tilt, the direction angles α and γ of line L must change. The new direction cosines for L are $a' = \cos(\alpha - \theta)$, $b' = \cos \beta$, and $c' = \cos(\gamma + \theta)$. To tilt the plane by an angle $-\theta$, the new direction cosines are $a' = \cos(\alpha + \theta)$, $b' = \cos \beta$, and $c' = \cos(\gamma - \theta)$. Points on p' must satisfy the equation

$$a'x + b'y + c'z + d = 0 \quad (3)$$

where $d = -(a'x_I + b'y_I + c'z_I)$.

4. APPLICATION

Implementing the concepts described in Section 3 is straightforward. Figure 5 shows the control panel in 3DM which provides the user with plane creation and tilt functions. A user may create an initial plane by selecting a *slice direction* in x , y , or z . Selecting the *z-slice direction*, for example, allows the user to create a plane parallel to the *xy-plane*. Similarly, clicking on slice direction y allows the user to create a plane parallel to the *xz-plane*. The user then selects a point of reference Q on the image body. The desired plane through point Q is created and displayed for the user; an example is shown in the left image of Figure 6.

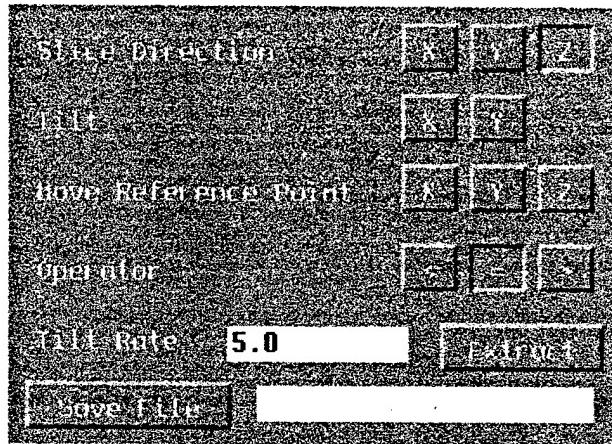


Figure 5. Plane control panel

The user then has the option of *tilting* the plane in either the x - or y -direction, by the tilt rate (in degrees) selected by the user (5 degrees, as shown), and in either the positive or negative direction by clicking on the left or the middle button of the computer mouse. The right image of Figure 6 shows the original plane tilted forward, i.e., in the positive y -direction, by an angle of approximately 10 degrees.

Implementation proceeds as follows. When a user selects a slice direction and a point of reference Q , a plane is defined and the direction angles α , β , and γ of the normal line L through Q , as well as the corresponding direction cosines a , b , and c , are established. Subsequent user clicks on the x - or y -tilt buttons result in changes in direction angles θ_x , θ_y , and θ_z which are added to the current direction angles and new direction cosines are computed. The new plane is defined using equation (2) and 3DM scans the image points identifying those which lie on the plane. The selected points are then displayed, measured, or used in another operation.

Tilted planes have proven to be useful in several ways. First, the user can take a variety of measurements such as preferred waist circumference (shown in Figure 6), include bicep, diaphragm, and neck circumferences. These measurements require that the plane containing the slice through the body be at some angle with the torso or upper arm respectively. The degree of the angle depends entirely on the definition of the measurement and how that definition is interpreted relative to the actual position of the body segment in question. Allowing the user to modify the direction and amount of tilt provides the control needed to place the slice exactly where the user wants it.

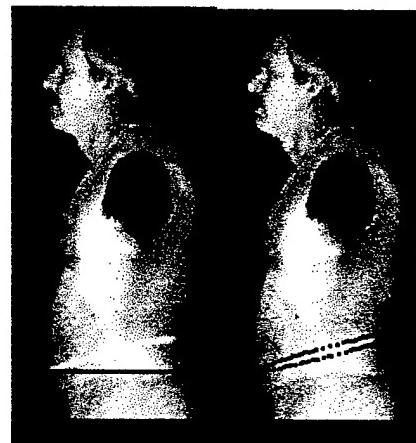


Figure 6. Plane creation and tilt

Second, the user can manually segment the body with precision. A tilted plane can be used quite effectively, as one might use a scalpel, to separate and isolate specific segments of the body. The easiest way to do this is to use the tilted plane function with two other 3DM functions, one which allows the user to hide one or more sections of the image temporarily, and a second to select and eliminate a section of the image (using the operator buttons "<" or ">" and "Extract" shown in Figure 5). Using these functions in sequence, the user can make precise cuts through the image. The result is that, without much effort, the user is able to carve out a specific segment of the image for subsequent analysis. A segment can be saved separately from the original image, or measured independently using all of the measurement tools available in 3DM, or further segmented if necessary. Figure 7 shows an image segmented into five parts: arms, legs, and torso.

A third benefit of a tilted plane function is that it can assist the user in analyzing the form of the body and classifying the body in terms of body shape, for example back posture (erect, regular, head bent forward, stooping) or shoulder slope (high, half high, regular, sloping, very sloping, extremely sloping). The plane selected by the user defines a specific slice through the body and the points on the plane can be identified, displayed in profile, and mathematically analyzed (Figure 8). 3DM provides a function which analyzes and shoulder slope of an image given a starting reference point, the center back point at neck. The results are shown in Figure 9.

Finally, tilted planes allow the user to eliminate extraneous and unwanted points often generated by a 3D scanner. Such additional points may appear in the digitized image for a number of reasons, for example poor lighting. Approximately 75% of 240 images currently being used with 3DM were discovered to contain unwanted artifacts. Tilted planes allow the user to eliminate such points quickly and to replace the original image with a clean image.

5. CONCLUSIONS AND FUTURE WORK

In summary, tilted planes have proven to be quite useful in manipulating and manually measuring 3D whole body scans. The computational requirements to create and tilt a plane are quite modest, resulting in rapid, almost immediate, response to user button clicks. Moreover, tilted planes continue to prove useful in current 3DM development work involving automatic detection of landmarks and automatic measurement. For example, observation of a sequence of planes parallel to the *xy-plane* through the upper torso provides clues to locating the center back point at neck. Successful automatic location of this point then leads to automatic back posture and shoulder slope classification.

6. ACKNOWLEDGEMENTS

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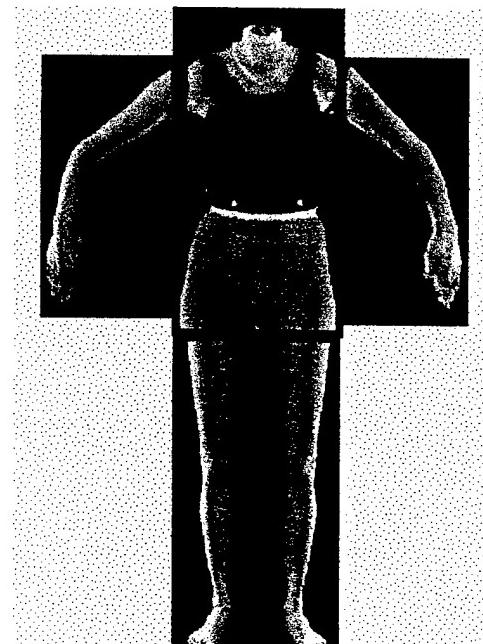


Figure 7. Segmented image

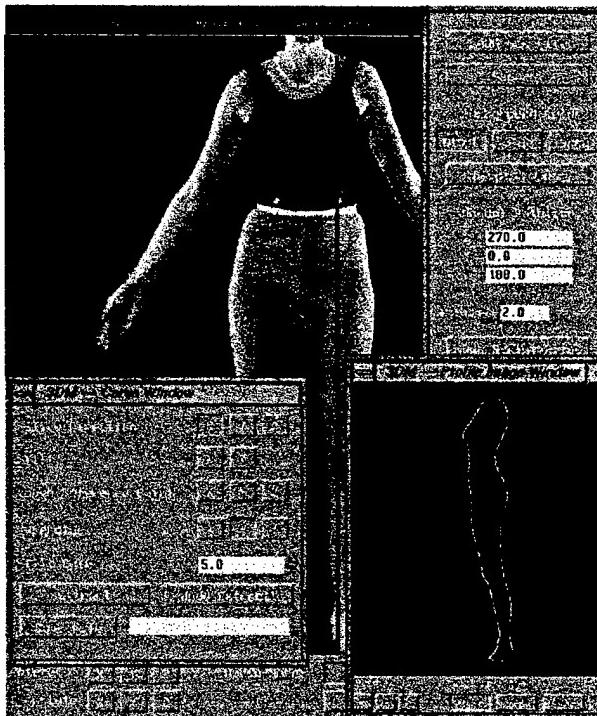


Figure 8. Profile slice through an image

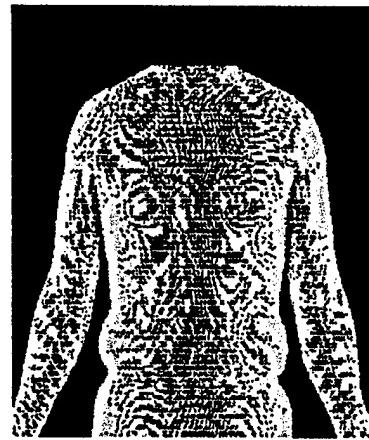


Figure 9. Shoulder slope

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